Neutrinos CAN violate CPT!

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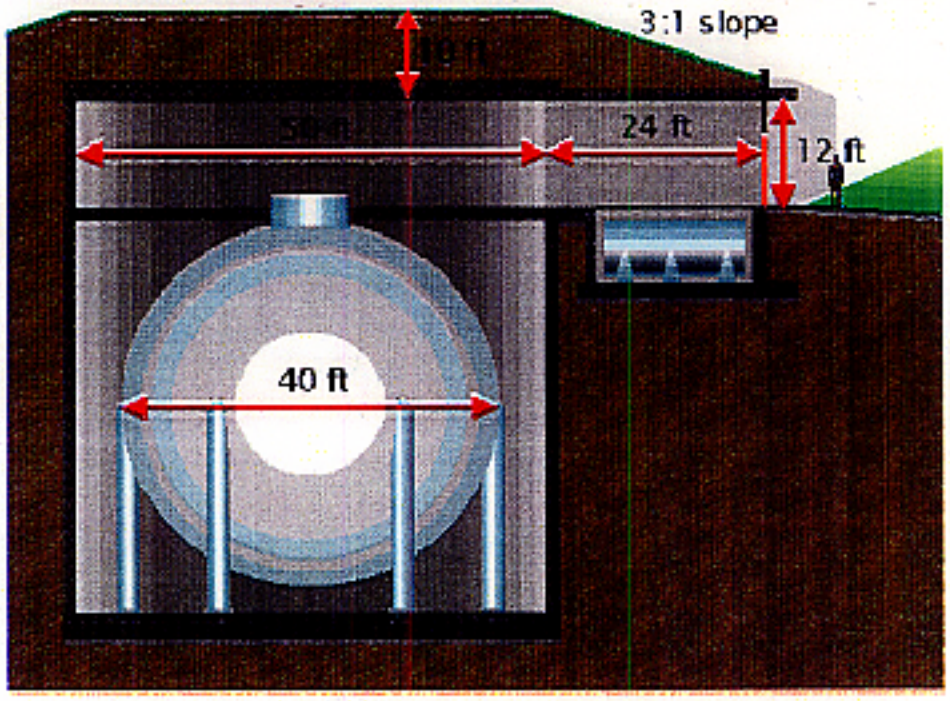
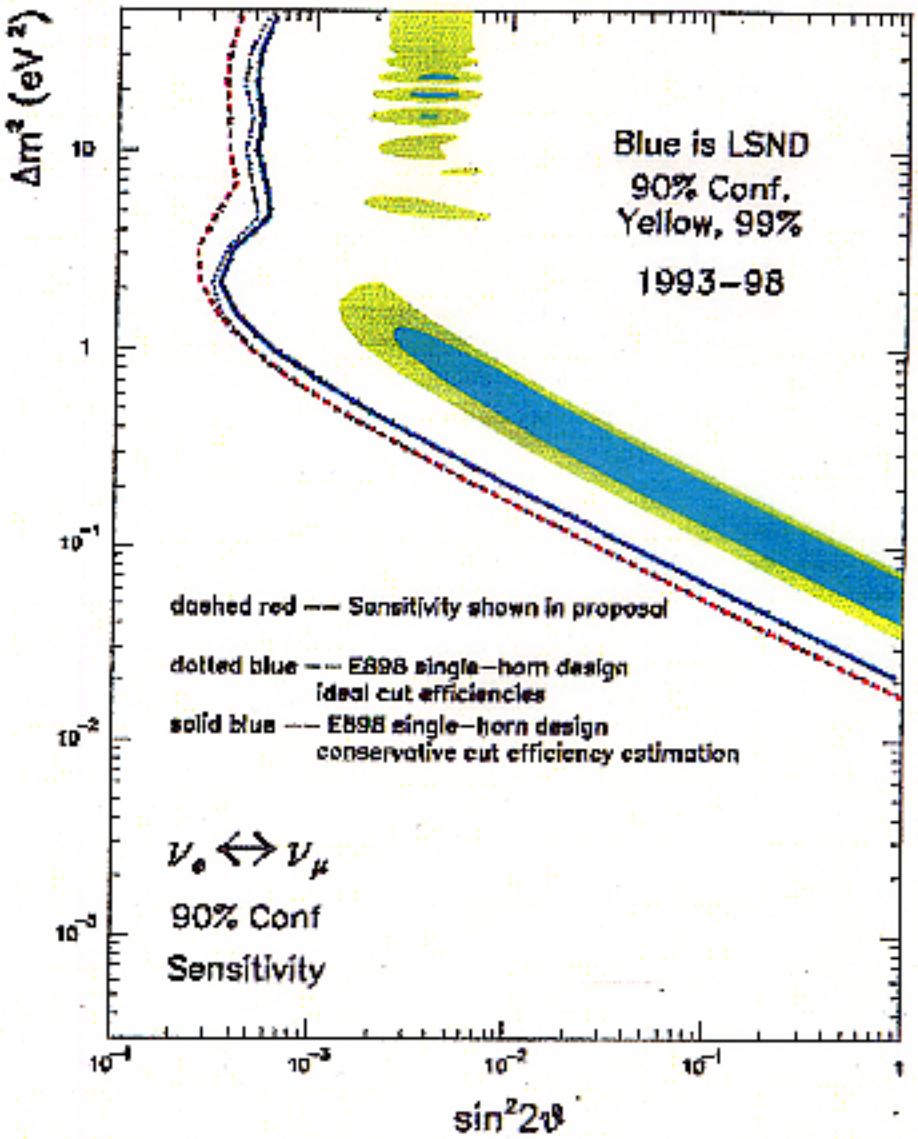
- ~~CPT~~ has the potential to explain all the ν anomalies without enlarging the ν sector
- ~~CPT~~ in the Dirac mass terms preserves Lorentz invariance but generates independent mass terms for ν and $\bar{\nu}$
- dramatic predictions for the upcoming experiments
- promising new mechanism for baryogenesis

$\bar{m}_3$
LSND
m_3
$\bar{m}_2$
atmospheric
atmospheric
m_2
$\bar{m}_1$
solar
m_1
Legend:
ν_e $\bar{\nu}_e$
ν_μ $\bar{\nu}_\mu$
ν_τ $\bar{\nu}_\tau$

How can we get $\not{CPT}$?

- Theoretical motivation for $\not{CPT}$ starts with string theory.
- In braneworld models of string phenomenology, the ν sector is the most likely messenger of $\not{CPT}$ to the rest of the SM
- The generic candidates for the bulk fields which act as messengers of $\not{CPT}$ are
  - (i) gravity
  - (ii) right-handed neutrino
- if ν's are the messengers of $\not{CPT}$, we may evade all of the stringent bounds on SM $\not{CPT}$ from the kaon sector


3:1 slope
24 ft
12 ft
40 ft


Blue is LSND
90% Conf.
Yellow, 99%
1993–98
dashed red — Sensitivity shown in proposal
dotted blue — E898 single–horn design
ideal cut efficiencies
solid blue — E898 single–horn design
conservative cut efficiency estimation
$\nu_e \leftrightarrow \nu_\mu$
90% Conf
Sensitivity
Δm^2 (eV^2)
$\sin^2 2\vartheta$

KAMLAND, A REACTOR NEUTRINO EXPERIMENT!

Reactor Site	Distance (km)	# of reactors	Therm. Power (max) (GW)	Max. Flux (10^5 $\bar{\nu}_e$ /cm^2/s)	Max.Event rate events/kt-year
Kashiwazaki	160	7	24.6	4.25	348
Ohi	180	4	13.7	1.90	154
Takahama	191	4	10.2	1.24	102
Hamaoka	214	4	10.6	1.03	84
Tsuruga	139	2	4.5	1.03	84
Shiga	81	1	1.6	1.08	89
Mihama	145	3	4.9	1.03	84
Fukushima-1	344	6	14.2	0.53	44
Fukushima-2	344	4	13.2	0.49	40
Tokai-II	295	1	3.3	0.17	14
Shimane	414	2	3.8	0.10	8
Ikata	561	3	6.0	0.08	7
Genkai	755	4	6.7	0.05	4
Onagawa	430	2	4.1	0.10	8
Tomari	784	2	3.3	0.02	2
Sendai	824	2	5.3	0.03	3
Total		51	130	13.1	1075

Table 3: Expected contribution of different reactors to the neutrino rates detected in KamLAND in the case of no oscillations. The event rate in the last column has been calculated assuming no oscillation and 100% "live time" for each reactor. Thermal power, flux and event rates are all given for the maximum operation of the reactors. Typically, annual averages are about 80% of the maximum.

BASELINE: 85.3% OF SIGNAL FROM 140-344 km

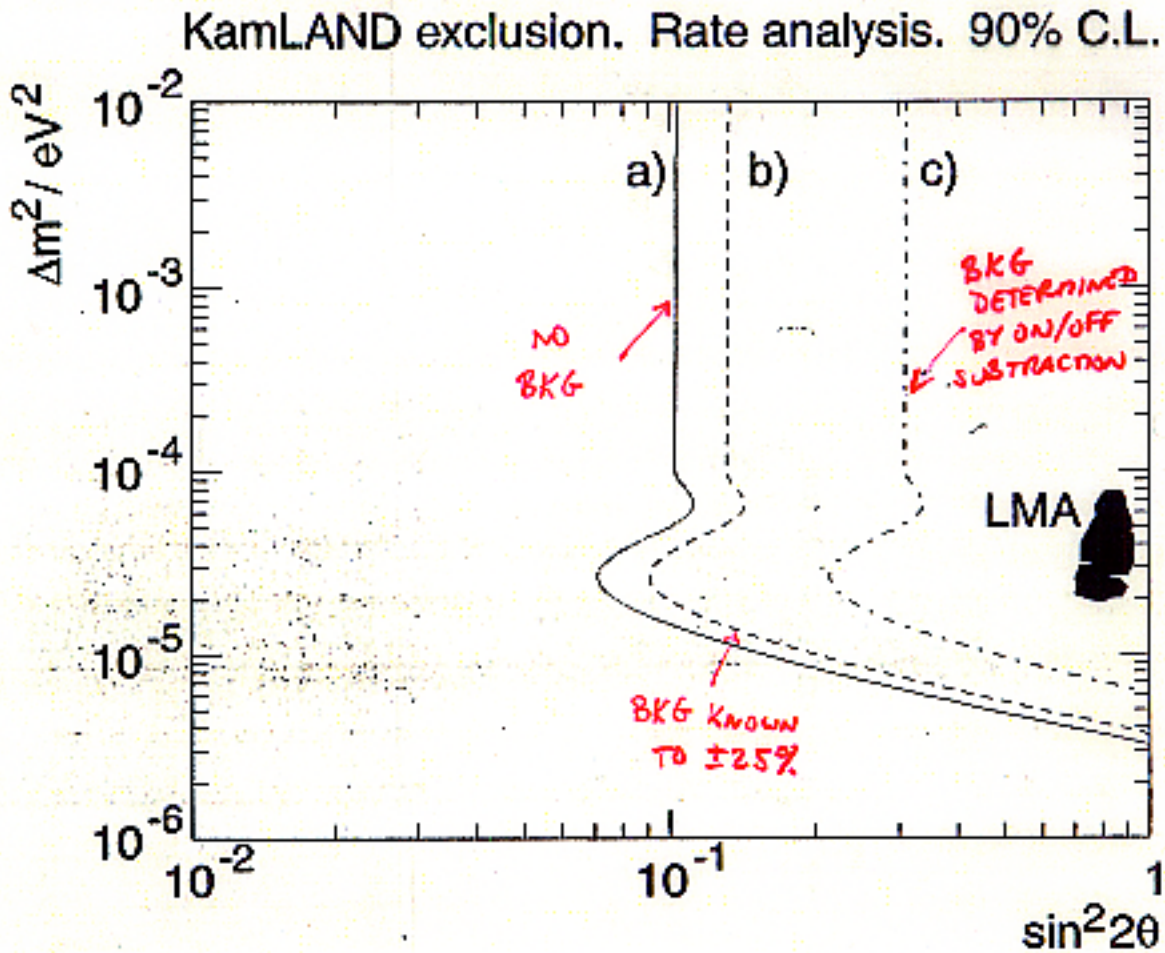


Figure 8: Sensitivity of the neutrino oscillation experiment to be performed at KamLAND. The curves represents the 90% CL sensitivity one can reach with 3 years of running with 78% of the maximum power flux. The following assumptions about the background level and its uncertainty have been made: a) ideal case; no background. b) signal-to-noise 10:1, background known to ±25%. c) signal-to-noise 10:1, background determined by subtraction through reactor on - off.

we predict Kamland will <u>not</u> see an oscillation signal

why? in our ~~CPT~~ scenario

$$P_{\nu_e}^{\text{survival}} \cong 1 - 4|U_{e3}|^2\left(1-|U_{e3}|^2\right)\sin^2\left(\frac{\Delta m_B^2 L}{4E}\right)$$

atmospheric but suppressed by $|U_{e3}|^2 \ll 1$

$$- 4|U_{e1}|^2|U_{e2}|^2\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

solar

but

$$P_{\bar{\nu}_e}^{\text{survival}} \cong 1 - 4|\bar{U}_{e3}|^2\left(1-|\bar{U}_{e3}|^2\right)\sin^2\left(\frac{\Delta \bar{m}_{13}^2 L}{4E}\right)$$

$$- 4|\bar{U}_{e1}|^2|\bar{U}_{e2}|^2\sin^2\left(\frac{\Delta \bar{m}_{12}^2 L}{4E}\right)$$

LSND but suppressed by $|\bar{U}_{e3}|^2 \approx 1$

atmospheric but $|\bar{U}_{e1}|^2, |\bar{U}_{e2}|^2 \ll 1$ (unitarity)

Problem: a negative KamLand result could also mean that solar Δm^2 is smaller

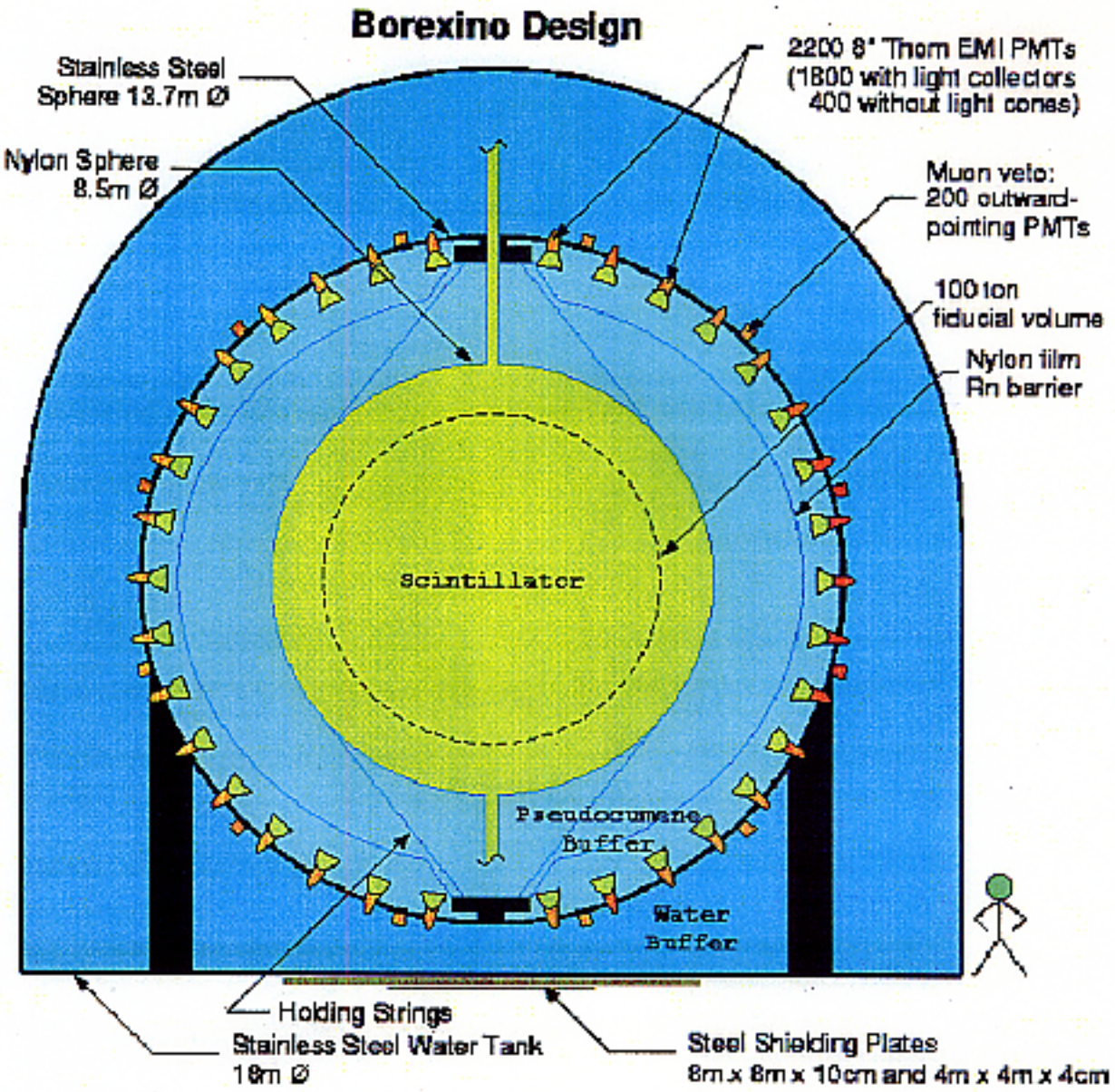
solar "LMA" $\longrightarrow$ solar "LOW"

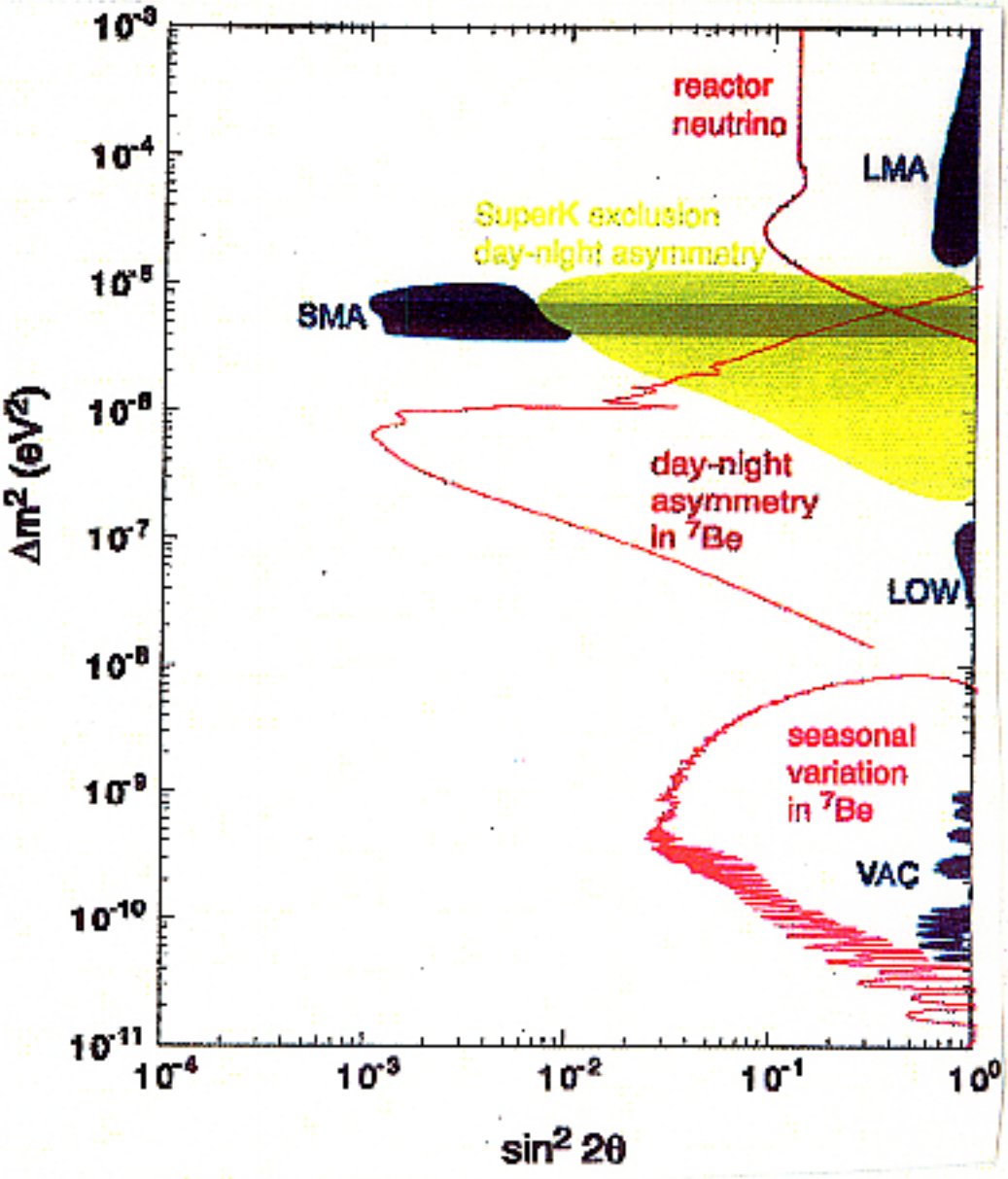
$\sim 10^{-5}\ eV^2$ $\qquad$ $10^{-7}\ eV^2$

to distinguish this from ~~QT~~

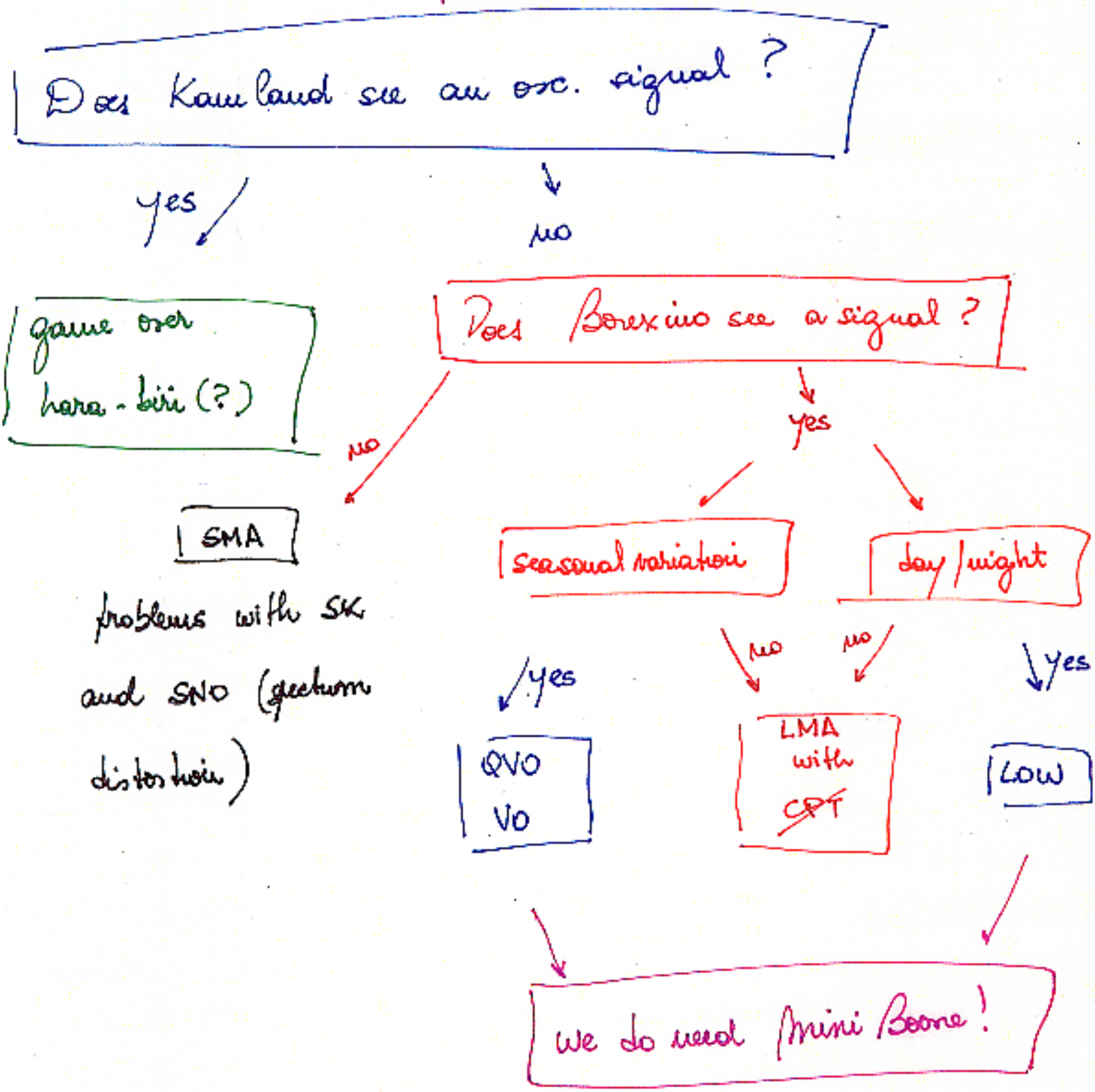
we need

Borexino!


Borexino Design
Stainless Steel Sphere 13.7m Ø
Nylon Sphere 8.5m Ø
2200 8" Thorn EMI PMTs (1800 with light collectors 400 without light cones)
Muon veto: 200 outward-pointing PMTs
100 ton fiducial volume
Nylon film Rn barrier
Scintillator
Pseudocumene Buffer
Water Buffer
Holding Strings
Stainless Steel Water Tank 18m Ø
Steel Shielding Plates 8m x 8m x 10cm and 4m x 4m x 4cm


reactor
neutrino
LMA
SuperK exclusion
day-night asymmetry
SMA
day-night
asymmetry
in ^{7}Be
LOW
seasonal
variation
in ^{7}Be
VAC
Δm^2 (eV^2)
$\sin^2 2\theta$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

Who needs MiniBoone?



A model of ~~CPT~~ for ν masses

Any Lorentz invariant theory of Dirac - Weyl fermions conserves CPT.

recall $\psi_{\pm}^{D}(x) = u_{\pm}(p)\, e^{-ipx}$

where $(\not{p} - m)\, u_{\pm}(p) = 0$

Let's invent a new kind of fermion, built from spinors which obey

$$(\not{p} - m\,\epsilon(p^0))\, u_{\pm}(p) = 0$$

but still satisfy $p^2 + m^2 = E^2$ (K.G)

Dirac theory $\left.\begin{matrix} u_+(p) \\ u_-(p) \end{matrix}\right\}$ are written $\begin{matrix} u(p) \\ v(-p) \end{matrix}$

$$(\not{p} - m)\, u(p) = 0$$

$$(-\not{p} - m)\, v(p) = 0$$

"homeotic" $\psi^h(x)$ $\quad (\not{p} - m)\, u(p) = 0$

$$(\not{p} - m)\, \tilde{u}(p) = 0$$

$$\psi^h(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \sum_s \left[a_p^s\, u^s(p)\, e^{-ipx} + b_p^{s\dagger}\, \tilde{u}^s(p)\, e^{ipx} \right]$$

Dirac eqn is replaced by

$$i \not{\partial}\, \psi^h(x) = \frac{-im}{\pi} \int dt' \frac{1}{t - t'}\, \psi^h(t', \vec{x})$$

The action of the free homeotic theory is nonlocal

(too bad ?)

no! remember that $\left\{a_{\vec{p}}^{r}, a_{\vec{q}}^{s+}\right\} = \left\{b_{\vec{p}}^{r}, b_{\vec{q}}^{s+}\right\} = (2\pi)^3 \delta^3(\vec{p}-\vec{q})\delta^{rs}$

and

$$H = \int \frac{d^3p}{(2\pi)^3} \sum_s E_p \left(a_p^{s+} a_p^s + b_p^{s+} b_p^s \right)$$

and

$$Q = \int \frac{d^3p}{(2\pi)^3} \sum_s \left(a_p^{s+} a_p^s - b_p^{s+} b_p^s \right)$$

is a conserved charge from the global $U(1)$ symmetry of the action

and the theory is Lorentz invariant !

So the <u>free</u> homeotic theory = <u>free</u> Dirac theory

however CPT is realized in a different way

Dirac $\psi(x) \xrightarrow[CPT]{} \gamma_5 \psi^*(-x)$

homeotic $\psi(x) \xrightarrow[CPT]{} i\gamma_2\gamma_5 \psi(-x)$

Now suppose that ν_L is a standard Dirac-Weyl fermion (it must be!)

but introduce a ν_R which is the RH part of a homeotic fermion

ν_R is a SM singlet so it is our "natural" (best, only) candidate to be different

in such a scenario, a mass term

$$m\left(\bar{\nu}_L^{D}\,\nu_R^{h} + \bar{\nu}_R^{h}\,\nu_L^{D}\right)$$

is hermitian but violates CPT !!

gives

$$2m\; a_p^{D+} a_p^{h} + 2E_p\; a_p^{D+} b_{-p}^{h+} + h.c$$

compared to Dirac mass term

$$m\; a_p^{+D} a_p^{D} + m\; b_p^{D+} b_p^{D}$$

* if LSND is confirmed ν theory is in trouble

* MiniBoone <u>or</u> Kamland + Borexino <u>could</u> point strongly to ~~CPT~~

* there is <u>at least</u> one simple field theory model of ~~CPT~~ neutrinos